

Steps towards sustainable manufacturing through modelling material, energy and waste flows

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Abstract

A sustainable society cannot be realised without more efficient approaches and technologies which must in part be provided by manufacturing. Available literature covers the principles for making manufacturing more sustainable, but there is little, if any, practical guidance to show how to apply these principles. Lower level guidelines are required to provide guidance on systematically analysing manufacturing facilities and to assist with the identification and selection of improvement opportunities. This paper reports on work to develop guidelines for Material, Energy and Waste (MEW) process flow modelling to support the pursuit of sustainable manufacturing. Using qualitative MEW process flow maps of a case facility, data was collected to build a spreadsheet model aligned to each of the MEW process flows. The quantitative analysis provided detailed insight into the MEW process flows within the system and assisted with the identification and selection of environmental efficiency improvements. The key learning points from conducting the analysis generated a set of guidelines to aid the analysis of manufacturing systems, using MEW process flow modelling. This paper documents the approach developed and the environmental performance improvement opportunities identified in the case facility.

Keywords

Process mapping, sustainable manufacture, zero carbon, material energy & waste modelling

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1. Introduction

A sustainable society must live within its means and use energy and materials in a way that will not compromise the standards and health of future generations [1]. Substantial improvements in the efficiency in which finite natural resources are used, and reduction of the wastes and emissions generated through their use, are required. A sustainable society cannot be realised without more efficient approaches and technologies which must in part be provided by manufacturing. Whilst the existing industrial system has helped to create the high standard of living which is enjoyed today in developed countries, merely using its existing configuration to produce these technologies is no longer appropriate [2]. As global living standards continue to rise; the challenge for manufacturing is to meet a constantly increasing demand for products whilst using less material, less energy and generating less waste [3].

Organisations that pursue more environmentally friendly products and operations will recover costs quickly [4] and contribute to competitive advantage [5] rather than suffering a burden [6]. Indeed, as material, energy and waste costs rise, environmental efficiency improvements will have greater benefit than ever before. Those that do not improve will suffer higher costs from waste disposal and non-compliance with punitive legislation [7]. Significant benefits from an environmental focus have been shown [8] and forward thinking companies that prepare for this future will thrive, while the rest will be left behind [9].

For manufacturing companies that have recognised the need for change, their challenge becomes understanding how it can be achieved. Research has been carried out to address this challenge [10, 11, 12], however, in general most research is generic and high level. The literature covers the principles for making manufacturing operations more sustainable, but there is little, if any, practical guidance available showing how to apply these principles. Lower level guidelines are required to aid manufacturers in making changes in their factories in order to improve environmental efficiency. The methodology must provide detailed guidance on systematically analysing individual manufacturing processes and assistance with the identification and selection of improvement opportunities.

Process flow modelling could be the basis for the creation of a suitable approach by mapping the lifecycle of Material, Energy and Waste (MEW) process flows. This has been achieved at a generic level [7] and has potential for use at a company level. MEW process flows are the physical resource inputs and outputs to the facility, and their efficiency within a manufacturing system could be measured financially and in terms of carbon emissions. This paper introduces an implementation approach developed and illustrates its application in a case company.

2. Aim and method

The aim of this work is to develop guidelines for Material, Energy and Waste (MEW) process flow modelling to support the pursuit of more sustainable manufacture.

The method used was to review available literature to establish the principles of sustainable manufacturing and the approaches to their deployment. Based on earlier literature review, it was known that available detailed approaches for manufacturing operations were sparse and therefore this work was necessarily inductive to draw from practice and generalise. From the literature review an initial approach for modelling MEW flows was developed and deployed in a case company to capture the qualitative and quantitative process flow data. This data was then analysed to assist in the identification of improvement opportunities. The result was both potential savings for manufacturing operations by taking a sustainability perspective as well as key learning points that were used to generate practical guidelines for others to use.

In scope are the production operations and supporting facilities of manufacturer. Efforts to reduce the environmental impact through supply chain configuration, product design, material selection, product use and product end of life are out of scope. Wider issues relating to consumerism and business models are also out of scope.

3. Literature review

3.1 Sustainability and business

Brundtland [1] defines sustainability as “meeting the needs of the present generation without compromising the ability of future generations to meet their own needs” (p. 8). Sustainability is the goal of sustainable development and this is described as “types of economic and social development that protect and enhance the natural environment and social equity” ([13], p.3). To be physically sustainable, Daly [14] identifies three rules which must be met: harvest or extraction rates should not exceed regeneration rates; waste emission rates should not exceed the natural absorption capacities of the ecosystems into which they are emitted; regenerative and absorption capacities are considered to be natural capital, and failure to maintain these capacities is natural capital consumption, which is not sustainable. Today, none of these rules are being met. The consequences of this have been the key environmental issues identified by Esty and Winston [15] of climate change, energy, water, biodiversity, toxics, air pollution, waste management, ozone, oceans and deforestation. In addition, materials sourcing and cost are also causes for concern, particularly for manufacturing businesses.

Environmental sustainability is of significant relevance to all sectors and presents both risks and opportunities for businesses [16]. Elkington [17] depicts the sustainability challenge as “an unprecedented source of commercial opportunity for competitive companies, through technological innovation and improved eco-efficiency”. A sustainable business model is one which recognises the triple bottom line (3BL) of social justice (People), environmental quality (Planet) and economic prosperity (Profit) [17]. This means that whether the justification for improved environmental performance is concern for the environment itself, management of the risks associated with sustainability, or to capitalise on the associated opportunities, it is essential to recognise the importance of sustainability and to adapt business models accordingly.

3.2 Linking environmental and financial performance

Traditional thinking in manufacturing companies suggests that the minimum amount of work should be done in order to meet environmental regulatory compliance, as going beyond this will increase costs [18]. Manufacturers accept environmental excellence can lead to extensive benefits, but have found the cost of complying with environmental regulation, or best practice targets, can be high [19]. Notably, the survey by the Economist Intelligence Unit found that "... 69% believe the link [between financial performance and commitment to sustainability] is strong in the long term (5-10 years), and companies worldwide are moving sustainability principles into their core policies and practices" [20]. Additionally, Yang et al [21] found that environmental performance positively impacts on financial and market performance.

Forward thinking manufacturing companies have recognised that whilst in the short term, improved environmental efficiency may lead to increased costs in some areas, in the long term it will lead to significantly improved financial performance and is now a prerequisite to make a business sustainable. As material and energy costs (as well as their subsequent waste disposal) costs rise, the cost of inaction towards environmental efficiency improvements may cost more than making the improvements themselves.

There are an increasing number of examples of savings that companies have made, for example:

- Brandix reduced water usage by 58% and reduced energy usage by 46% resulting in 30-40% reduction in operating costs [1]
- Ford (Global Operations) reduced their energy usage by 30% and water usage by 43% [22]
- Sony reduced their CO₂ emissions from electricity use and facility heating (European operations) by 93% over 10 years [23]
- Rolls-Royce reduced solvents by 51%, reduced greenhouse gas emissions by 24% and increased the proportion of solid waste sent for recycling by 63% over a period of 10 years whilst doubling turnover [24].

Analysis of the improvements found showed that each of them fits into one or more of the three material, energy and waste (MEW) process flow categories, which can be directly linked to the economic dimension. Clearly, drawing less inputs and generating less waste outputs which must be paid for, or paid to dispose of, is of financial and environmental benefit. These examples collectively suggest that a focus on the MEW process flows within a facility provides a basis upon which environmental and financial performance improvements can be pursued.

3.3 Approaches for achieving environmental efficiency improvements

Having recognised the importance of the environment to businesses and seen examples of real benefits being achieved, it is necessary to understand the approaches available for pursuing improvements. As awareness of environmental concerns has grown, so has the literature and research activity in this area.

The Natural-Step (TNS) defined by Broman et al. [25] is a broad strategic framework for organisations which provides high-level guidance for sustainability investments and initiatives. According to this framework, there are systems conditions which must be met for society to become sustainable (the ecosphere must not be subjected to increasing concentrations of waste, over-harvested or used inefficiently), and a strategy is required to change the organisation in order to fulfil these conditions (understanding the conditions, understand a company's relative position, creating a vision and specifying an action plan). TNS intentionally does not prescribe specific actions hence companies must define the tactical and operational level changes required, possibly combining with other approaches to realise environmental improvements.

For the concept of Industrial Ecology (IE), Graedel [26] describes three model types that capture resource flows from the ecosphere to the technosphere and back. In the first model (linear, type I) the resources flow (material and energy) from the ecosphere into the technosphere and then waste is returned to the ecosphere with the assumption there is unlimited capacity to absorb the industrial waste. In the second model (quasi-cyclic, type II) there is a certain degree of cycling of resource in the technosphere and thereby reducing the burden on the ecosphere to provide

resource and absorb waste. Hence material and energy flows are reduced, as well as waste flows. In the third model (cyclic, type III) the highest degree of cycling through closed loop occurs to enable self-sufficiency and reliance only on renewable energy inputs. IE concept has not been applied at factory level [27] and therefore whilst conceptually it is of relevance there is no guidance for its deployment in companies.

Sustainable Manufacturing (SM) [10, 28, 29] (based on environmental conscious manufacturing) is broad in scope, taking a high level view of manufacturing and including all three elements of the triple bottom line. SM and its predecessors looks beyond the boundaries of a single facility and considers the entire material cycle from material extraction through processing and use to subsequent disposal [4, 30]. A lot of SM research has focused on product development and end-of-life management in order to keep products within the technosphere after the “Use” phase. There has been less SM research activity focusing on improving specific manufacturing systems, especially the component production and assembly stages. This has meant that SM does not provide a methodology for manufacturers to generate improvements within their own facilities [31].

Zero Carbon Manufacturing (ZCM) [7] can be viewed as a constituent element of sustainable manufacturing which is focused on the tactical and operational levels of an organisation. ZCM takes the perspective of the manufacturer and seeks to improve the environmental performance of their system by understanding the process flows within it. This is achieved by examining the manufacturing processes, the surrounding building and the associated facilities at a systems level through Material, Energy and Waste (MEW) process mapping. A black-box view of the system and its components is adopted and the focus is on examining the process inputs and outputs. Opportunities are sought for reusing outputs elsewhere in the system as inputs to other processes, to reduce net environmental impact. When viewed in isolation, manufacturing processes cannot be zero carbon, but when considering such processes as part of a wider system; it is possible to achieve net carbon reduction [32].

4. Development of an approach to address sustainability at factory level

It is apparent from the literature that most approaches for progressing towards sustainable development are generic and high level. There is a lack of guidance and tools for manufacturers to identify improvement opportunities within their own factories. The use of material, energy and waste (MEW) as a basis for improvement has potential for analysis given that manufacturers express their improvements in those forms and there are high level concepts in which to frame the work. Any analysis must address both the qualitative MEW flows as well as the quantitative flows.

In order to develop the MEW process flow modelling technique, it is first necessary to determine the most appropriate process flow mapping tool to be used. To pursue environmental efficiency improvements, the systems within a manufacturing organisation must be represented so that the complexities and interactions are reduced to a manageable level for analysis. Process maps can be jointly analysed by Facilities Maintenance and Manufacturing Engineering Specialists, to highlight where the input of one activity can be provided by the output of another activity, in order to reduce overall consumption. Traditionally these departments would be focused on reducing waste within their own areas rather than adopting an integrated view of the facility and reducing waste at the system level.

IDEFO is a suitable format for representing MEW process flows, providing a structured representation of activities (boxes) within a system with their corresponding Input, Control, Output and Mechanism (ICOM) (arrows). Inputs enter on the left of the activity box, outputs leave on the right, mechanisms (activity enablers) enter from below and controls (legislations and policies) feed from above. Conveniently, each activity can be hierarchically decomposed to a lower level to provide a more detailed representation of that activity. The approach is standardised but users must possess basic knowledge of the technique in order to understand it.

The use of a structured process mapping tool followed by detailed quantitative analysis is useful in understanding interactions within a system [33]. Quantitative analysis of MEW flows can be done using a top down, or bottom up approach. The

top down approach involves examining the total MEW flows and costs in a given time period and attempting to trace the usage and generation to particular assets. The bottom up approach, which is used in this work, involves mapping MEW process flows from a systems level perspective to understand the inputs and outputs of the system and the individual processes within it.

Lean production [34] is an approach with supporting tools to reduce waste and improve flow by focusing on delivering value to the customer. Lean approaches for lean have the potential as a base for looking at wider production resources, namely: look see, process mapping, data collection, data analysis, improvement opportunities, implementation and review. However, whilst sustainable manufacturing practices are compatible with lean, primarily through waste reduction, it is not a given that lean practices will improve environmental performance [21] through reducing waste and reusing resources across the spectrum of a manufacturing system necessary. Lean in practice and as a result of the typical toolset is focused on the primary flows to customer, not the support infrastructure to achieve them. This is supported by empirical evidence. For example, as a proponent of lean, Toyota is seen as the benchmark for lean adoption, however has made massive reductions in resource consumption since it adopted its eco-factory focus in its sustainable plants over the last decade [35].

The literature review failed to uncover techniques for gathering MEW process flow data and quantitative modelling. The closest examples are Life Cycle Analysis (LCA) (see ISO14040) and adapted versions of Value Stream Mapping (VSM) [36], both of which are product stream rather than production function focused. Another example is that of de Ron [37] which lacks the production system depth and case evidence presented here.

These areas currently represent gaps in the literature which this research is intended to fill. The following steps were judged to be appropriate as a starting point for modelling and the key learning points gained from their deployment will be used to develop generic guidelines:

- Step 1. Factory walk around to understand the manufacturing system
- Step 2. Creation of IDEF0 map for the manufacturing system flows and verify
- Step 3. Brainstorm the MEW flows to enrich documentation
- Step 4. Establish IDEF0 MEW flows
- Step 5. Gather quantitative data against each MEW flow
- Step 6. Create quantitative model and verify
- Step 7. Analyse results from model to identify candidate areas for improvement
- Step 8. Develop solutions and make recommendations
- Step 9. Implement improvements

For solutions deemed to lead to improved environmental performance, methods are required to prioritise which ones to pursue to ensure maximum benefit. For energy and waste flows, it is necessary to evaluate them against the energy and waste hierarchies and to consider the technical, practical, and economic aspects, as shown in Figure 1. For material flows, only technical, practical, and economic aspects can be considered as a hierarchy does not exist.

5. Industrial case

The case company is a leading supplier of high value products and services through the manufacture of equipment for industrial, process, research, and analytical instrumentation applications. The company employs several thousand people who specialise in the design, manufacture, servicing and support of high technology industrial equipment. The business operates multiple manufacturing and service hubs across the globe which are associated with different product divisions. The case facility for this work is in the UK and primarily includes precision machining and assembly processes. The facility is subdivided into different manufacturing cells based on the processes utilised and products produced

The data for the analysis was gathered by walking the factory floor and meeting with stakeholders from Operations Management, Facilities Maintenance and Machine Tool Maintenance. IDEF0 maps were produced to represent the systems used within the facility. Brainstorming was carried out to identify the potential MEW process flows to look for prior to the second walk around the factory. The brainstorm and factory

walks were used to create the IDEF0 maps showing the MEW process flows within the facility. The completed maps were reviewed to ascertain the quantitative data required for each process flow. After the data was gathered, it was reviewed to determine if it was of suitable quality to create a quantitative model.

The intention of the model was to present the quantitative data in a logical way for analysis and for identifying improvement opportunities. Having established that understanding MEW process flows was essential for pursuing improvements, the quantitative data in the model was presented using the same format as the qualitative maps. The anticipated level of detail in the model was to provide data that could be used to answer questions such as how much electricity was consumed over a given time period by a particular asset, and whether the consumption was the same in all modes of operation?

Examination of the quantitative analysis of the process flows led to the application of Pareto analysis to rank the process flows by value to establish which area was best to focus improvement efforts, noting that it is not only necessary to look at the quantities of the MEW process flows but also the ability to influence them. Following the ranking the approach described for figure 1 was adopted.

6. Results

Using the provisional approach presented earlier the application of MEW process flow modelling was applied in the case company. Step 9 (implementation) is omitted.

Step 1. Understanding the manufacturing system

One author was already familiar with the manufacturing system. A walk around the production area was necessary however to look at the system not from the eyes of a lean specialist improving flow by focusing on value add but from the view of MEW flows. The walk draws from the benefits of Gemba practised by adopters of lean management where going to see the problem an essential early step.

Steps 2. Creation of IDEF0 MEW maps and verification

To produce the IDEF0 process maps it was necessary to set the level of abstraction for viewing the manufacturing system and whether to map a specific product, a family of products, or generic products within the factory. The parts produced in the case facility were divided into generic categories, and were assumed to be produced in the same way using generic processes. An example process map is shown in Figure 2. The map shown was the simplest of the 10 maps developed for all the production cells in the facility. It became clear during the case that it is necessary to then verify the maps by repeating step 1 to ensure complete and correct capture.

Figure 2 shows how castings are machined and inspected prior to delivery to the downstream cell. High level MEW categories are captured on these maps. For example, castings (material) and utilities (energy) feed a machining operation resulting in production waste and consumable waste. The energy waste (heat) is not shown in the map at this stage as it is not an obvious or visible output.

Step 3. Brainstorm to enrich MEW flows

Brainstorming was carried out to identify the MEW process flows throughout the facility prior to structured MEW process flow mapping using IDEF0. An example brainstorm of typical MEW process flows is shown in Figure 3. Following the rules of brainstorming all MEW flows were captured and judgements were not made on whether or not they were valuable enough to include.

Step 4. Establish IDEF0 MEW flows

For the IDEF0 MEW process maps, the flows were divided into Material, Energy and Waste categories, as shown in Table 1. The same categories were also used for the quantitative analysis.

Steps 5-7 Quantitative MEW data gathering, modelling and analysis

Although quantities were not given on the qualitative IDEF0 maps and brainstorms, a review of these documents indicated that the machining area had the highest consumption and waste generation as it had the greatest number of process flow arrows. This would also have been intuitive whilst walking the case facility, as there were not many different types of processes used. In other facilities, where numerous

types of machinery are used, it would not have been as clear; hence the value of the mapping increases.

A spreadsheet model was constructed to quantify the MEW process flows. The structure of the quantitative model is shown in Figure 4 and subsequent figures show example screenshots of the quantitative data (Figure 5) and Pareto analysis (Figure 6). The qualitative maps were presented at the front of the model to illustrate the evolution from IDEF0 maps to a spreadsheet model and for reference during the quantitative analysis. The summary page collates the data from the variable usage asset sheets and presents them in terms of MEW process flows. The constant usage assets are analysed on the summary page. For variable usage assets that were dependent on production levels, the same level was used throughout to ensure relevant comparisons were made. A combination of strategies was used to collect data, including analysis of retrospective MEW data, asset performance calculations and empirical measurements.

The charts developed showed that the key material, energy and waste process flow costs for machined parts and castings, were electricity, and scrap respectively. These were then investigated further. It is also possible to conduct a Pareto analysis by asset rather than by process flow type. Taking this approach helps to identify particular assets with high consumption and waste generation.

Step 8. Develop solutions and make recommendations

From the analysis and ranking, three areas were investigated and recommendations proposed for improvement. It should be noted that the improvements areas listed are not initially obvious and may not have been uncovered had classic lean approaches alone been deployed.

1. **e-Stop.** Machining centres consume large amounts of electricity whether they are in operational mode (metal cutting) or idle mode (waiting). In operational mode, the electricity consumption cannot be influenced as it is governed by the machine design and part machining requirements. To save electricity in idle mode, the machine could be shutdown or be switched to the emergency stop (e-stop) state

after a defined period of time at the end of a cycle. Calculations showed that this could save the case facility around €115k/year. Enabling e-stop should not compromise accuracy providing the machine is warmed up again before producing more parts. A process capability analysis needs to be conducted to prove this.

2. **Coolant.** A coolant management processes is used in the case facility. The most expensive element of the process is to dispose of waste oil. To reduce the amount of oil that needs to be disposed of, a coolant recycling machine could be employed. Large plants typically spend €1.5M/year on replacing fluids; therefore significant savings can be made [16]. Investment and cost savings are not available for the case facility.
3. **Compressed air.** Compressed air usage is an expensive yet essential part of many manufacturing processes. A number of steps can be taken to reduce the environmental and economic cost of compressed air. McGuire [40] suggests a number of steps to reducing the environmental and economic cost of compressed air including controlling leaks, controlling temperatures, reducing pressures and using better lubricants. Investment and cost savings are not available for the case facility. The estimated cost is €12k/year at facility level.

The benefits of this investigation were as follows:

- a) The process enabled improvement opportunities to be generated with quantified cash savings by purchasing less resource.
- b) The options generated, whilst could be considered compatible with the lean philosophy, would not have been generated by the traditional application of lean methods. Power, consumables, etc. are not the typical focus of lean improvement work.
- c) Whilst the solutions initially were not obvious to those on the shop floor, they were identified by, and traceable to, the improvement method used.

7. Developing MEW process modelling guidelines

The application of the initial approach to modelling and analysing MEW flows was developed in the absence of detailed guidelines for working towards sustainable manufacturing but in the context of high level, well disseminated concepts. Key learning points from the application of the initial approach were used to develop the guidelines shown in Figure 7. These guidelines are described in more detail next.

7.1 Walk factory to understand systems within the factory

The factory walk includes the manufacturing, building and facilities systems, individually or by multidisciplinary teams including operations management, maintenance and manufacturing engineering. Repeat as required.

7.2 Qualitatively map manufacturing processes

Capture the systems using a structured process mapping technique. An IDEF0 map with 3 levels of decomposition is recommended. The operational characteristics of the systems should be understood prior to considering MEW process flows. Although IDEF0 has been specified for the qualitative mapping stage, the desired result could be achieved using other hierarchical methodologies if preferred.

7.3 Brainstorm likely MEW flows in systems

Brainstorming is beneficial for identifying the MEW process flows for each area. This unstructured method helps to quickly capture some of the MEW flows that will be present, but not necessarily the exact locations. It will indicate the area that the MEW IDEF0 maps and quantitative modelling should focus. Brainstorming also allows MEW flows that are not directly related to the processes that have been defined to be captured.

7.4 Select area for MEW quantitative modelling

To maximise improvement opportunities, the largest MEW generation and usage areas should be modelled first. When focusing on a small area of a facility, care must be taken when apportioning the inputs and outputs of shared assets. These assets provide MEW process flows, such as compressed air or water, for the entire facility, so by focusing on a smaller area, assumptions must be made regarding the

proportion which should be allocated to the chosen area if metering is not available. Sensitivity of the model to variation in these assumptions should be tested.

7.5 Qualitatively map MEW flows in chosen area

Qualitative mapping of the MEW process flows captures information in a structured manner which drives the quantitative analysis. Accuracy of the maps should be confirmed with Manufacturing Engineers and Facilities Maintenance, as their perspectives may be different.

7.6 Identify shared process and non-process related MEW flows in chosen area

Mapping identifies process related MEW flows. Shared process related MEW flows, such as compressed air, should also be captured. It is not possible to represent non-process related MEW flows such as, lighting or heating, for the building using IDEF0. Brainstorming is recommended for capturing this information qualitatively.

7.7 Identify assets in chosen area

The processes and MEW flows on the qualitative maps must be linked to the assets in the selected area.

7.8 Gather high level MEW data for assets

It is essential to develop a basic understanding of how each asset works, particularly for shared assets that were not investigated in the process mapping stage.

7.9 Determine constant and variable usage assets

All assets have variable consumption and waste generation levels. For modelling purposes, some assets can be simplified by treating them as constant usage whilst maintaining a suitable level of accuracy. Data will be required from the asset manufacturer in order to accurately model variable usage assets. Less data is required for constant usage assets.

7.10 Determine low level data gathering strategies

In preparation for detailed quantitative analysis it is necessary to determine suitable low level data gathering strategies of (in order of increasing effort):

- a) Analysis of retrospective MEW data

- b) Asset calculations
- c) Empirical measurements
- d) Benchmark against similar companies or available case studies

7.11 Create and validate MEW quantitative model

At the earliest opportunity set the scope of the MEW quantitative model to drive its creation and to validate it appropriately. The qualitative analysis will suggest areas of the facility to focus the quantitative analysis, as high consumption or waste and generation will be reflected in the process maps. Data availability will also influence what can be achieved; if there is more data about one area then greater insights can be made.

7.12 Analyse results and identify improvement opportunities

Pareto analysis identifies which of the MEW process flows have the greatest impact. The costs can be represented per asset or per MEW flow.

7.13 Rank improvement opportunities

To rank improvement opportunities, it is necessary to look at the quantities of the MEW process flows and the ability to influence them. The energy and waste hierarchies are also useful for this purpose followed by consideration of the technical, practical, and economic aspects of each improvement.

7.14 Implement improvements

Standard project management techniques apply here.

7.15 Monitor improvements

Improvements must be monitored to ensure benefits are realised after the initial implementation and rebound effects do not occur.

7.16 Roll out guidelines and improvements to other areas/facilities

The methodology and improvements should be applied to other cells within the facility and to other manufacturing facilities in order to minimise environmental impact.

8. Discussion

The processes and flows that were observed by walking around the case facility were mapped first. This is in contrast to the recommended IDEF0 practice of producing the more abstract, top level diagram first and then decomposing down to lower levels with increasing detail. It was easier to map what had been seen during the walk rather than attempting to think abstractly about processes that were unfamiliar. The convention for IDEF0 is to show less than 6 processes per level of decomposition. The maps produced showed additional processes which added to their complexity but avoided any reduction in clarity from the cross-over of many arrows that could have otherwise occurred. The process walk and the use of process maps are complementary; the process walk captures the visible processes and generic process maps prompt for omissions such as waste (particularly heat waste) and checks for mass flow balance.

Retrospective data can be of value as a comparison to establish the accuracy of a quantitative model if the quality of the data is high. An issue found in the case study data was that available data often had missing data points or extreme outliers meaning manual correction was necessary by knowledgeable individuals. If there is a high degree of uncertainty in the data it is possible to attempt to cleanse it by removing anomalies, and confirming that the data collection frequency and resolution is appropriate. To facilitate meaningful comparisons, a disciplined approach to data gathering is required. Personnel tasked with gathering data do not necessarily have formal training in this area, or the awareness of the value of the data and its use in downstream activities. It is not necessary to conduct such detailed analysis on assets with low consumption levels and costs, however, identifying them does help educate staff. The work here provide guidance on the types of data to collect but does not completely address the gap in the literature of guiding the quality of data to collect, i.e. frequency, duration, detail and accuracy.

This work does not attempt to reduce scrap levels, but it does highlight both the cost of wasted material and also the cost of wasted production overheads, which are not traditionally considered. It will help to raise awareness, such that operators are

encouraged to be more careful when using expensive assets and parts. The same is true of swarf; the amount of swarf produced is not influenced directly, but by highlighting the associated costs, it encourages better product and process design to reduce swarf generation, and better management of what swarf is produced.

An alternative modelling strategy to adopt is to produce a model without any form of qualitative process mapping first. Whilst this could have been pursued, the maps made the quantitative model easier and quicker to construct. They offer a wider appreciation of the opportunities for system level improvements and provide confidence that all the MEW process flows have been considered. They are also easier to communicate than a complex quantitative model and in turn help build confidence with those affected by potential changes or those needed to give approval for change.

Process maps can only represent improvement opportunities related to the process itself. They do not directly identify non-process related opportunities for integrating MEW process flows such as rainwater harvesting or using waste water. The maps assist indirectly because as opportunities are sought for process related improvements, the scope of the search naturally evolves to include non-process related opportunities. One issue with the approach is that it guides improvements in areas that typical manufacturing engineers lack experience. This is in contrast to improvements in value-adding processes through the application of lean and other tools where engineers will have more experience and access to more examples. There is potential therefore to find ways of linking the guidelines presented to repositories of practices [41] that engineers can search for specific ideas. This particular case study was based on activities by manufacturing engineering, wider membership could have prompted how inputs and outputs identified in the process maps are provided and or can utilised respectively.

The number of opportunities for integrating MEW process flows by recovering wastes, such as heat or water, for use as inputs elsewhere in the system is dependent on the type of manufacturer. There will be more opportunities in process industries or other plants where the building is designed around the process. In such companies, assets have a long lifespan and are large in size, or have high

throughputs, meaning their locations tend to be fixed for the duration of their life. In smaller companies making lower volume parts, or smaller discrete products, more flexibility is required in their factory setup meaning the locations of their assets do not tend to be permanent. In larger companies the level of investment available will be higher meaning more sophisticated systems can be built around assets to maximise the recovery and recycling of wastes. This starts to move the focus of MEW modelling from Industrial Ecology Type I to Type II with a certain degree of recycling internally such as heat waste.

Applying the guidelines and improvement opportunities to facilities has the potential to reduce their environmental impact and improve economic performance. The improvements identified in the case directly impact on economic and environmental metrics through more efficient use of resources and lower waste output. The analysis results should be used to influence the design of new facilities, or the expansion of existing facilities, by integrating manufacturing, building and facility systems to reduce environmental impact.

It should be noted that the improvements offered by modelling MEW flows does not replace the use of lean techniques but complements them by broadening the scope beyond the value stream to less obvious, less visible improvement opportunities. Future opportunities, apart from the application of the approach in a wider range of companies, could come from understanding how to “mainstream” the approach to integrate the developments here with improvement approaches that focus on the value add processes to customer. The method developed here demonstrates the applicability of the approach to the particular case but the strength of this method over others is difficult to assess given the absence of published alternatives.

9. Conclusion

Manufacturers have a key role in aiding the transition towards sustainable development. Sustainability must be a key consideration for manufacturing organisations today, and its importance will only increase in the future. Some companies are already benefiting by managing the risks associated with

sustainability and capitalising on the opportunities. Improved environmental performance leads to larger profits, as operational costs are reduced.

Detailed methodologies are required to aid manufacturers in analysing their operations to identify and implement improvements within their factories to reduce environmental impact. The literature review revealed that these are not available and represent a gap in knowledge. The aim of this work was to develop guidelines for Material, Energy and Waste (MEW) process flow modelling, to support the pursuit of Zero Carbon Manufacturing (ZCM) and sustainable manufacturing to address the gaps.

The aim was achieved through qualitative mapping of the MEW process flows within a machining cell in a case facility. This was followed by the creation of a quantitative spreadsheet model and the definition of methods for selecting and implementing environmental improvement opportunities. Guidelines were produced by capturing what was learnt through the analysis of the case facility.

This work contributes to the state of the art by introducing guidelines to identify improvements not explicitly or typically identified by lean or other improvement approaches. Whilst the solutions derived are not novel, structured procedures to identify them, such as the one presented here, are new.

Through this work, potential future research directions have been identified. Firstly, improvement metrics are important but there is an absence of work on what effective metrics are and how they can be combined with existing key performance indicators to drive appropriate shop floor actions. Secondly, the work used bespoke spreadsheet models as there was an absence of available tools to support modelling and evaluation. Future tools developed need to be able to span the primary materials processing through to the support environment and be able to evaluate the inevitable trade-offs transpire. Thirdly, sustainable manufacturing solutions developed are typically derived locally from structured analysis of problems and there is potential for databases of sustainable practices to inform the solution generation to improve the solutions selected or reduce the time to establishing solutions. Finally, it is important that research is conducted on understanding and recognising that

compromises have to be made in implementing more sustainable manufacturing practices and the impact that reducing resources use has on production activities.

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Figure captions

Figure 1: Criteria for ranking solutions to improve environmental efficiency

Figure 2. IDEF0 map of cell selected for quantitative analysis

Figure 3: Brainstorm of MEW process flows in cell selected for quantitative analysis

Figure 4: Quantitative model structure

Figure 5. Summary sheet containing constant and variable assets and overall MEW (Section 2 of Model)

Figure 6. Example Pareto analysis chart showing energy flows (Section 4 of Model)

Figure 7: Guidelines for MEW process flow modelling

Table captions

Table 1: MEW process flow categories

Figures and tables

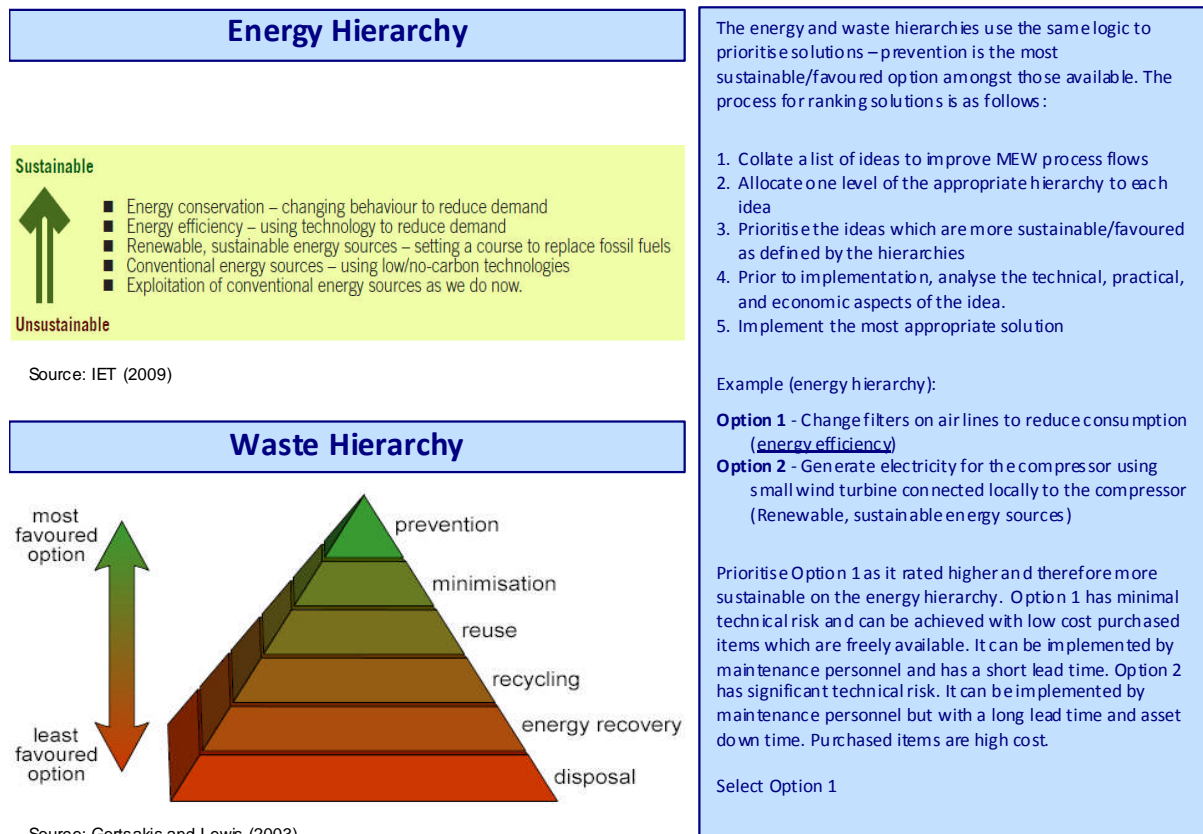


Figure 1: Criteria for ranking solutions to improve environmental efficiency

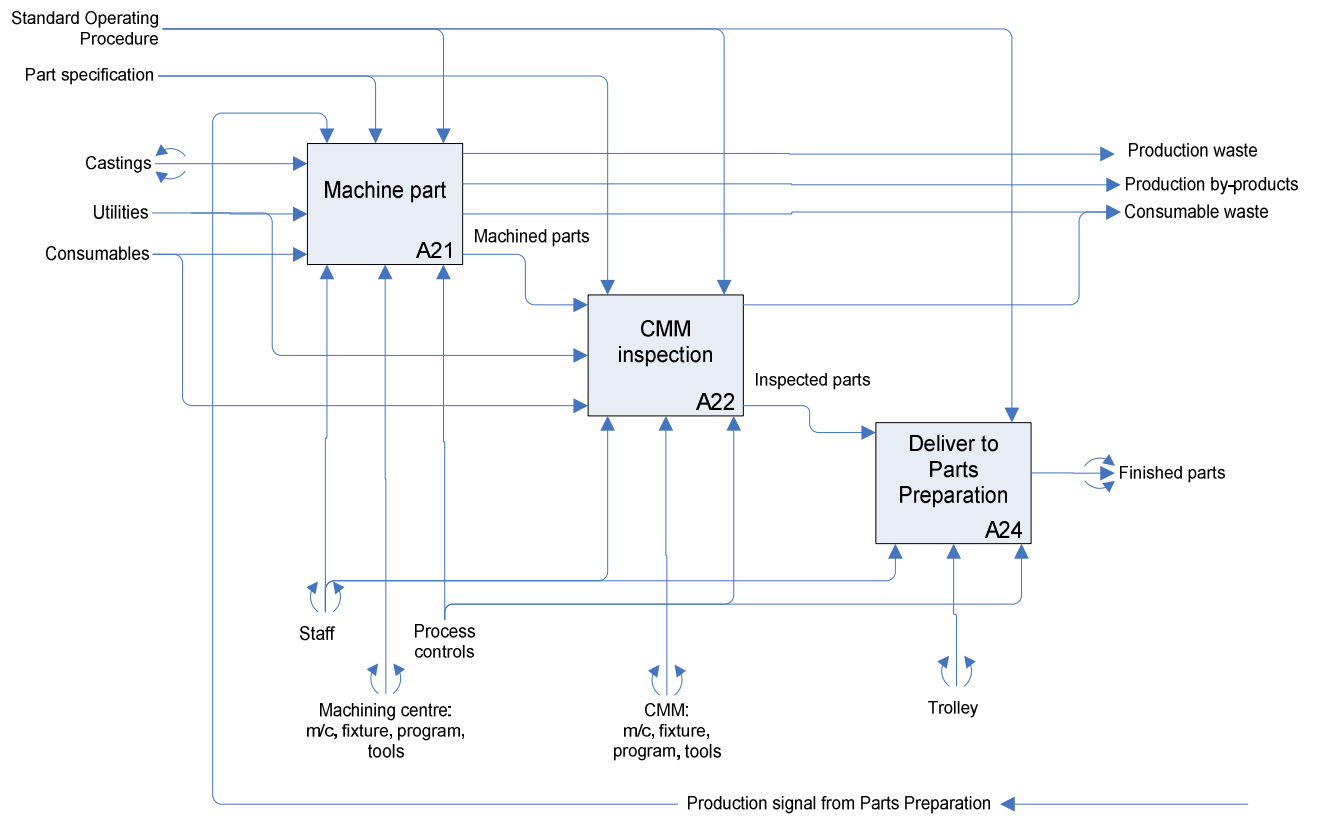


Figure 2. IDEF0 map of cell selected for quantitative analysis

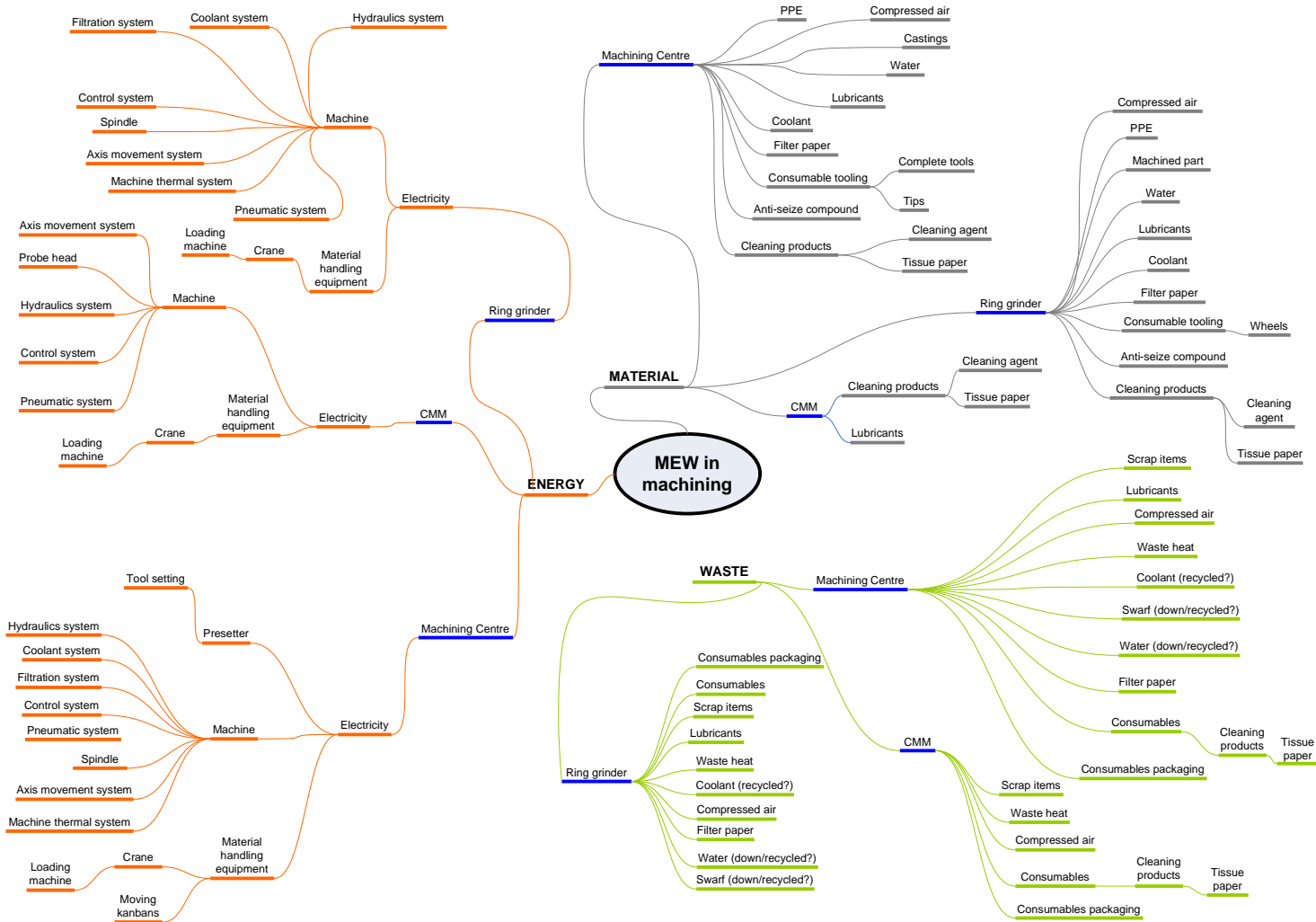


Figure 3: Brainstorm of MEW process flows in cell selected for quantitative analysis

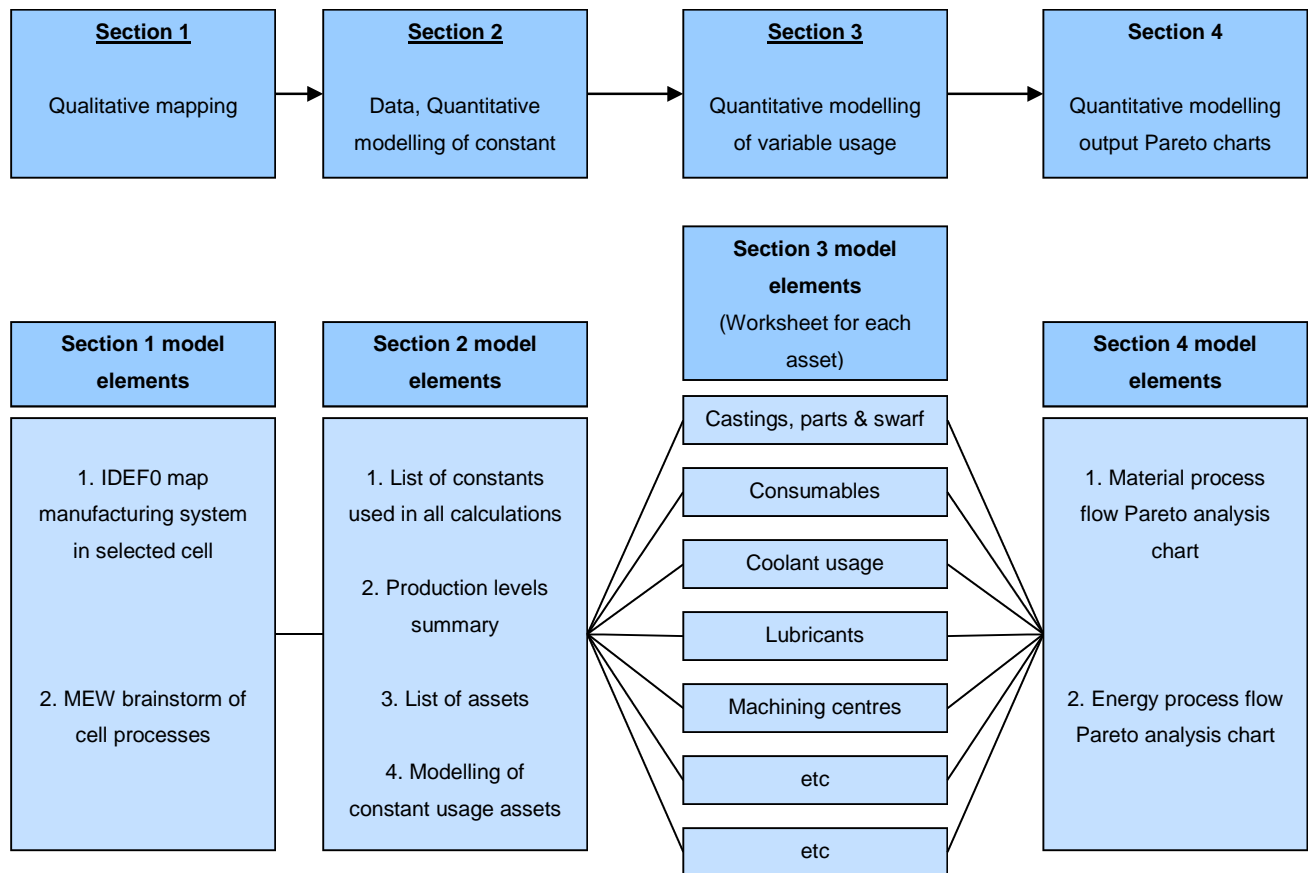


Figure 4: Quantitative model structure

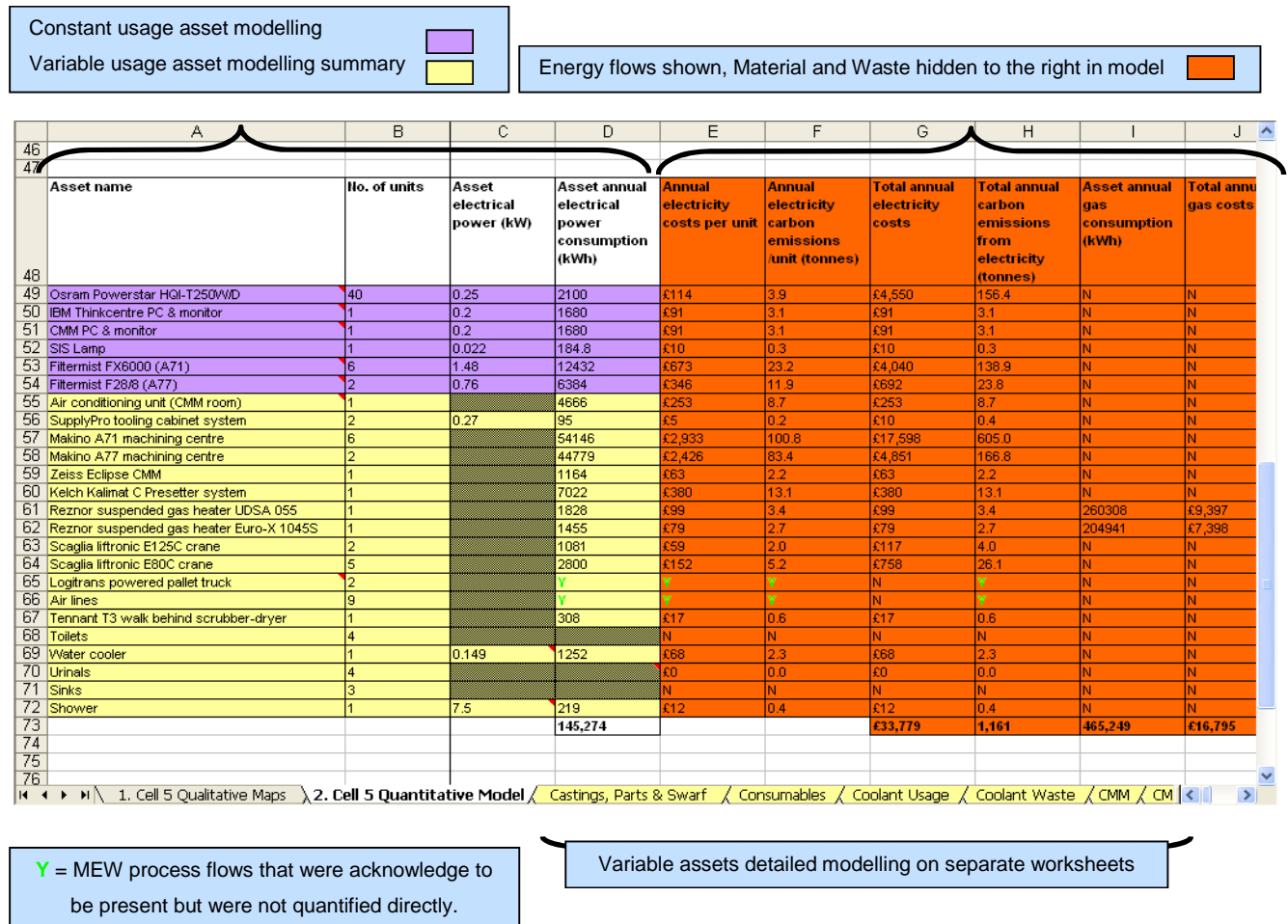


Figure 5. Summary sheet containing constant and variable assets and overall MEW (Section 2 of Model)

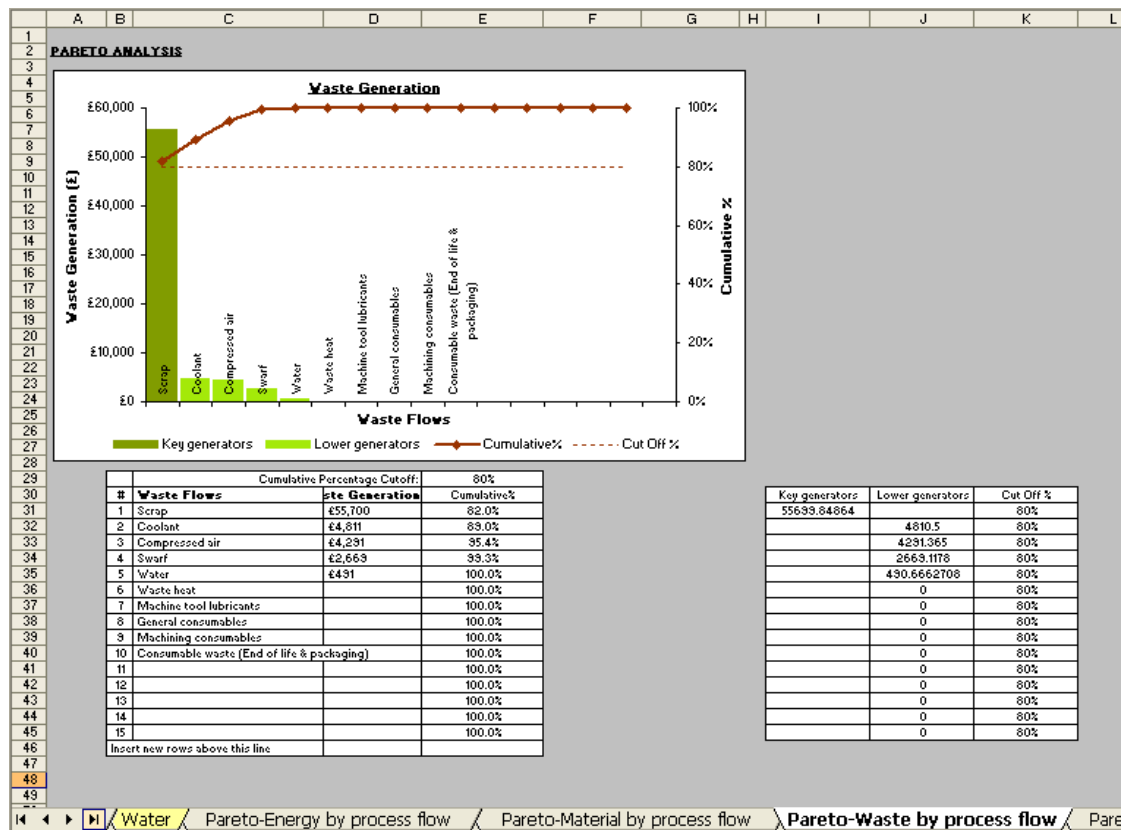


Figure 6. Example Pareto analysis chart showing waste flows (Section 4 of Model)

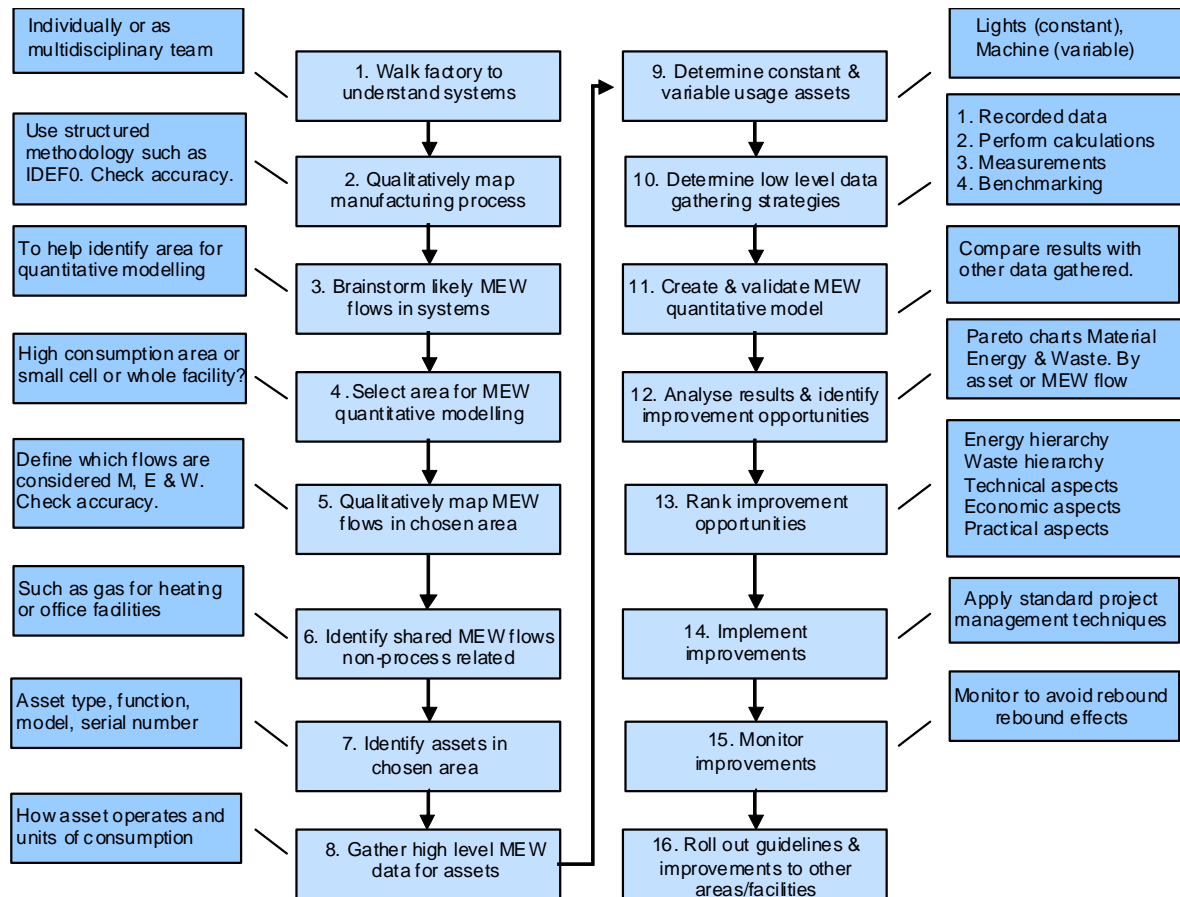


Figure 7: Guidelines for MEW process flow modelling

No.	Material Process Flows	Energy Process Flows	Waste Process Flows
1	Castings	Electricity	Machining scrap
2	Water	Gas	Swarf
3	Compressed air		Water
4	Coolant		Compressed air
5	Machine tool lubricants		Coolant
6	General consumables		Waste heat
7	Machining process consumables		Machine tool lubricants
8	Parts		General consumables (usage)
9			Machining consumables (usage)
10			Consumables (packaging)

Table 1: MEW process flow categories

Vitae

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